The Coggan Low Speed Wind Tunnel:

Design, Dimensions, and Operating Characteristics

Andrew R. Coggan, Ph.D.

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Introduction

In the spring of 2011 I went on a business trip that took me through Charlotte, NC. In the airport there I saw a replica of the Wright brothers' 1902 glider, of which I took pictures to show to my children when I got home. While doing so I explained to them how the Wright brothers were also important early pioneers in the use of wind tunnel testing. This led my then-6-y-old daughter to suggest that we build a wind tunnel, as she had seen other (older) kids do in a science program on television. The rest, as they say, is history…

General considerations and design principles

Although the wind tunnel was originally conceived as a father-daughter, science fair-type project, it soon became clear that the knowledge and effort required to build anything other than a rudimentary tunnel were such that this arrangement would be quite one-sided. My focus therefore changed to building something that could serve as a teaching tool for my (and other) children while also enabling me to satisfy my curiosity about certain cycling-related aerodynamic questions. After spending a fair bit of time researching the principles of wind tunnel design and construction, I set about attempting to build the best wind tunnel that I could while taking into consideration specific cost, time, and space constraints. Since I wanted to use it as a teaching tool, I also tried to make it as simple to understand and operate as possible – this in particular influenced the design of the balance, where I opted for a mostly mechanical system (except for the scale itself) rather than using, e.g., a force transducer and computer to collect data. Finally, although I am not a novice at building scientific equipment out of various materials, I would not claim to be a skilled craftsman, and do not own anything beyond your typical powered hand tools. (Indeed, I had to buy a hand-held jig saw just to cut a few key pieces..please don't tell my wife!) Thus, with the exception of the contraction I avoided the use of complex shapes, instead sticking to an easier-to-build "box" construction.

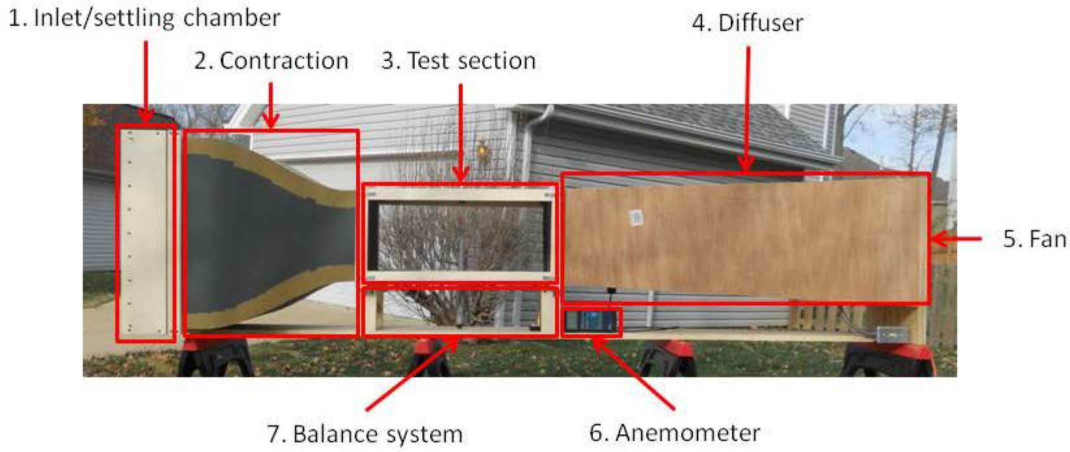
Overall design

Low speed (as in, those that operate at speeds <100 m/s, or at <Mach 0.3) wind tunnels can be of either closed-circuit ("racetrack) or open-circuit (i.e., ends open to the atmosphere) design. A closed-circuit design minimizes the energy requirement and hence cost of operating a tunnel and, at least in principle, makes it easier to achieve uniform flow. Building a closed-circuit tunnel, however, would have exceeded my space and monetary constraints, so I opted for an open-circuit design. Once that decision was made I had choose between building a "blower" or "suction" tunnel. The original Wright brothers' wind tunnel (http://www.wrightflyer.org/WindTunnel/testing1.html) was actually a blower tunnel, being equipped with an axial fan at what they euphemistically referred to as the "goesinta" end. A blower tunnel, however, performs best when powered by a centrifugal (radial) fan, as the latter introduces much less swirl into the downstream airflow and allows the test section to be readily interchanged to meet varying needs. Unfortunately, though, for a given volumetric flow capacity centrifugal fans (e.g., furnace blowers) tend to cost significantly more than axial fans. I therefore decided to build an open-circuit suction wind tunnel powered by an axial fan. Such a design is actually looked upon with some disdain by Bradshaw and Mehta, who emphasize that "an open-circuit tunnel . . . is really just a closed-circuit tunnel with a poorly-designed inlet" and

refer to it as a "K-12 project". In the context of my needs and constraints, however, this configuration actually made the most sense.

The finished wind tunnel is shown in **Fig. 1** below, with the specific components identified being discussed in the sections that follow:

Figure 1: Finished wind tunnel.



Specific components

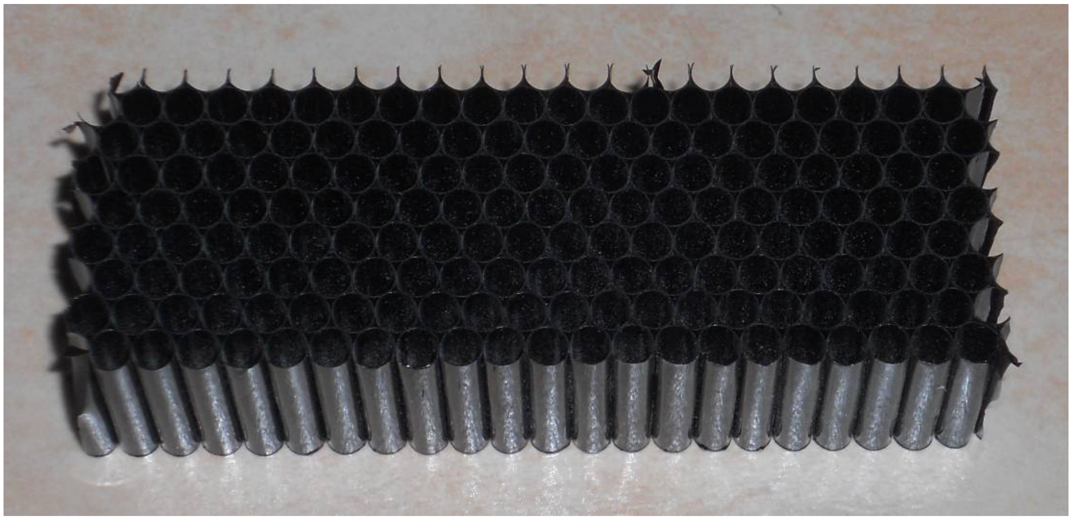
1. *Inlet/Settling chamber*

The purpose of the inlet and settling chamber is to align and smooth the air flow before it enters the contraction that follows. This is accomplished in part via a 610 x 610 mm piece of plastic honeycomb (**Fig. 2**; sourced from www.paxonpc.com for $50) comprised of approximately 36,000 individual cells, which serve to minimize transverse fluctuations in air velocity and "knock down" larger scale turbulent eddies.

Figure 2: View of front of wind tunnel showing black plastic honeycomb.

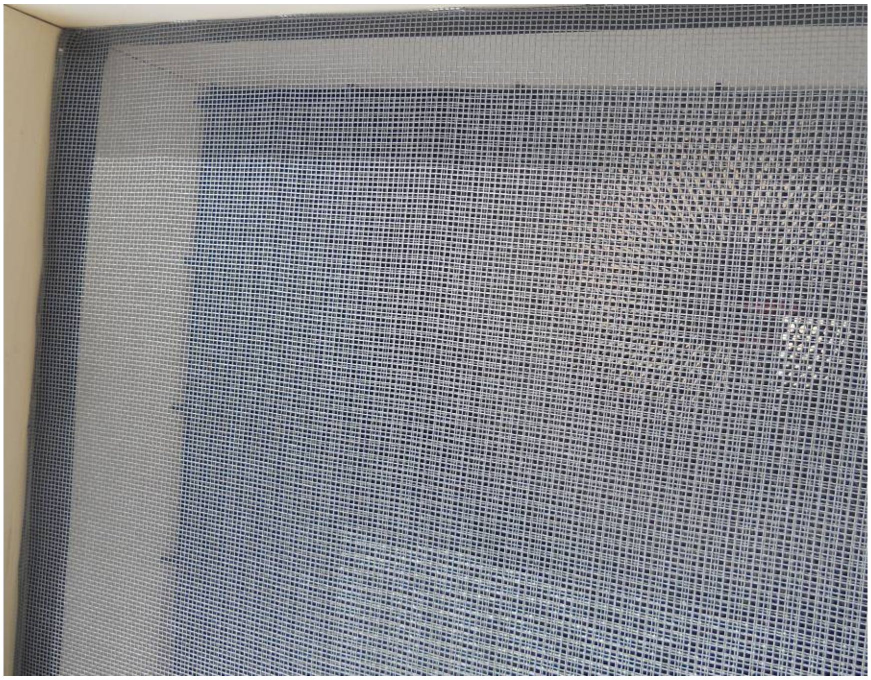
A close-up view of a scrap piece of the honeycomb is shown in **Fig. 3** below. Each cell is 3.175 mm in diameter and 25.4 mm deep.

Figure 3. Close-up of honeycomb material showing individual cells.



By itself, however, a honeycomb has limited effect on longitudinal variations in velocity and smaller scale turbulent eddies – in fact, it creates its own turbulence of characteristic scale, which would take considerable distance to decay. Thus, located behind the honeycomb are two anti-turbulence screens (**Fig. 4**).

Figure 4. View of anti-turbulence screens in inlet/settling chamber from downstream.



The first, made of wire, is held in place immediately downstream of the honeycomb by numerous zip ties around the periphery. The second, made of nylon, is simply stapled to the inside of the inlet/settling chamber, with the closely-trimmed edges and staples smoothed over with electrical tape. The 2nd screen is located 80 mm (25 mesh lengths) downstream of the 1st, thus allowing sufficient distance for the turbulence created by the 1st screen to decay before the air hits the 2nd screen. For the same reason, the 2nd screen is located 40 mm (also 25 mesh lengths) upstream of the entry to the contraction.

Along with the contraction (see below), these two screens would be expected to reduce the turbulence intensity (i.e., the root-mean-square of near-instantaneous variations in longitudinal velocity divided by the overall mean velocity) to <1% of that of the incoming air. Assuming that indoor room air has a turbulence intensity of 30-70%, the turbulence intensity in the test section is therefore *theoretically* expected to be 0.2-0.6%. This is similar to that found in many university wind tunnels, and consistent with Marshall's design criteria.

To permit easy access to the screens (for cleaning) and to the inside of the contraction (e.g., for demonstration purposes), the inlet/settling chamber is attached to the contraction via hinges as shown in **Fig. 5** below. The zip ties holding the 1st anti-turbulence screen in place are also evident.

Figure 5. Hinges attaching the inlet/settling chamber to the front of the contraction.

Note the thin spacers (made from scrap pieces of mat board) under the front leaf of each hinge – these serve to offset the frame of the inlet/settling chamber from the frame around the mouth of the contraction, such that their interior dimensions are perfectly aligned.

The inlet/settling chamber frame is also slightly smaller, to account for the thickness of the mat board used to build the contraction. A foam seal prevents any air from leaking in via the joint between the settling chamber and the frame around the mouth of the contraction.

2. *Contraction*

The purpose of the contraction is to smoothly accelerate the air exiting the (larger) inlet/settling chamber and direct it into the (smaller) test section. In the process, turbulence intensity is further reduced, as the overall mean velocity increases while near-instantaneous variations in velocity are little affected. Thus, within reason the larger the entry:exit area ratio of the contraction, the better, with ratios of 6:1 to 9:1 generally recommended for tunnels of comparable design. Based on this, I had originally planned on using a 9:1 contraction, which at least theoretically would have reduced the turbulence intensity by a factor of about 81 (i.e., 9^2). However, the plastic honeycomb was not available in a large enough piece to permit this. As well, I did not want to have to disassemble the tunnel to get it out of my basement for transport to, e.g., the local elementary school for the annual science night. Thus, I settled on building a 4:1 contraction out of mat board, as shown in **Fig. 6** below.

Figure 6. Side view of contraction made of mat board.

To help compensate for the smaller-than-theoretically-optimal contraction, as previously described I used two anti-turbulence screens instead of one as I had originally planned. The trade-off is a slightly (i.e., 5-10%) lower air velocity in the test section, which in turn means lower absolute drag forces. Thus, to help compensate for this I designed the sting/balance system to amplify the drag force by 2.5-fold prior to measurement (see *7. Balance System*).

As mentioned above, I built the contraction out of mat board, which proved to be nearly ideal for this purpose. I first cut a template of the desired profile (a 6^{th} order polynomial based on the work of Sargison et al.) out of thin plywood, then used this to guide my razor knife while cutting the mat board. I then stapled all four sides to the inside of the front frame, fixed the newly-cut edges in opposition using packing tape on the outside, and reinforced/sealed these corner joints from the inside with a bead of wood glue. Although the result is somewhat crude-looking from the outside, the inside walls of the contraction are smoothly curved as intended, as shown in **Fig. 7** below.

Figure 7. Inside of contraction.

The contraction is also surprisingly stiff and strong, thus allaying my fears that it would be fragile and thus easily dented, e.g., in transport.

3. <u>Test section</u>

The test section is, obviously, where objects are placed for testing, and thus is the portion of the wind tunnel where the air flow is desired to be most uniform. The ratio of width to height of a test section is generally chosen with the intended purpose of the wind tunnel in mind. For example, a wind tunnel intended for testing wing sections will usually be wider than it is tall (often in a ratio of 3:2), whereas a wind tunnel designed for testing of architectural models will normally be taller than it is wide. Since I wished to use the tunnel for a variety of purposes, however, I chose a square (305 x 305 mm) design. On the other hand, I chose the test section length (of 610 mm) to allow adequate space for development of uniform flow coming out of the contraction while still limiting overall growth of the boundary layer. (Some wind tunnel test sections are designed with angled (typically by 0.5 deg), moving, and/or slotted walls, to allow for growth of the boundary layer while keeping the size of the central working cross-section constant. For the sake of simplicity, however, I did not incorporate any of these more sophisticated design elements.)

I had originally intended to make the test section entirely out of clear Plexiglas®, with triangular fillets in the corners to minimize growth/migration of the boundary layer. In an attempt to minimize costs, however, I made the mistake of purchasing a single piece of acrylic at the local "big box" hardware store and having them cut it for me into four rectangular pieces. Unfortunately, their cuts were not exact, such that the four pieces did not mate perfectly. As well, obtaining the proper cement for joining Plexiglas® proved a bit difficult, due to restrictions imposed by environmental concerns. I therefore redesigned the test section to have Plexiglas® sides but a plywood ceiling and floor, held together by an external frame (**Fig. 8**). Also visible is the metal sting (mount), which protrudes through a hole in the bottom of the test section.

Figure 8. Test section with Plexiglas® sides and plywood top and bottom.

Although it is somewhat more difficult to see into the test section due to the opaque top and bottom, the clear sides at least are at a child's height when the wind tunnel is placed on a table or sawhorses, such that I still consider the end-result to be acceptable. Nonetheless, in the future I may rebuild the test section entirely out of Plexiglas® (with a few exceptions, I used only screws and not glue to construct the tunnel, to make such future modifications easier).

4. *Diffuser*

The purpose of the diffuser is to allow the air exiting the test section to expand and gradually slow down, thus reducing the dynamic pressure (kinetic energy) and increasing the static pressure. This reduces the current drawn by the fan motor or, alternatively, allows a higher speed to be achieved for a given motor/fan size and current draw. The angle included by the diffuser walls is generally limited to approximately 5° – maximum pressure recovery actually occurs at a somewhat greater angle, but the boundary layer is close enough to separation that the flow through the diffuser and hence the entire tunnel may become unsteady. This small angle combined with the desire to limit the overall length of a wind tunnel generally leads to an inlet:outlet area ratio of less than the value of three needed to recover 95% of the static pressure.

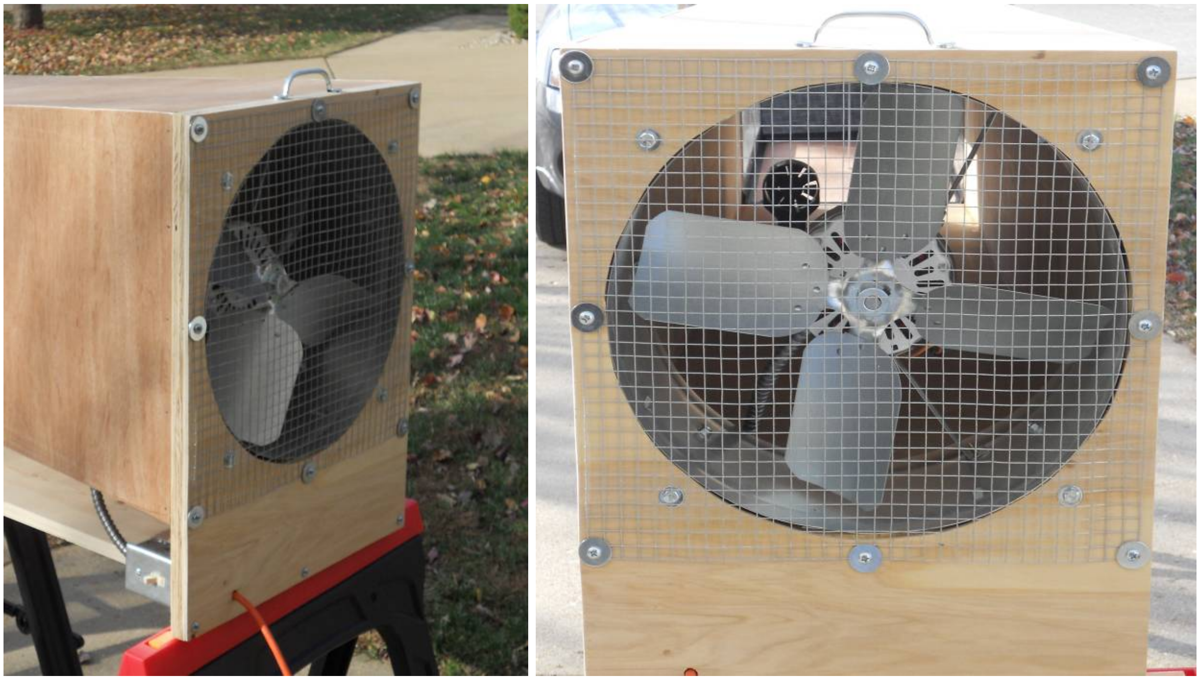
For the present tunnel the aforementioned ratio is 1.9:1, which was dictated by the cross-sectional area of the test section, the size of the fan, and the length of the half-sheets of plywood that I used to build the diffuser. The resultant included angle is 5.5° in either the vertical or horizontal plane (**Fig. 9**).

Figure 9. Diffuser section.

5. *Fan*

To power the wind tunnel I purchased the least expensive 14" gable (vertical) mount attic fan that I could find, discarded the thermostat, and rewired it to a simple on-off switch and power cord made from an outdoor extension cord as shown in **Fig. 10** below.

Figure 10. Fan.



Despite the relatively low cost ($80), the fan appears to deliver the 1650 ft^3/min flow rate claimed by the manufacturer (Ventamatic), at least once you consider energy losses throughout the tunnel (especially in the anti-turbulence screens). A multi-speed AC or, better still, a DC fan would be a better choice, as this would allow the tunnel to be operated at varying wind speeds/Reynolds numbers. Such choices, however, would have been more expensive (especially a DC fan). Depending on the use seen by/ultimate fate of the wind tunnel, though, I may still upgrade the fan and/or fan motor at some point. For example, using the fan shown here: http://insulmation.stores.yahoo.net/quatfan.html would, at least on paper, increase the tunnel speed by 11% (thus increasing the drag forces by 24%), but alone would cost about as much as I spent on the entire wind tunnel project.

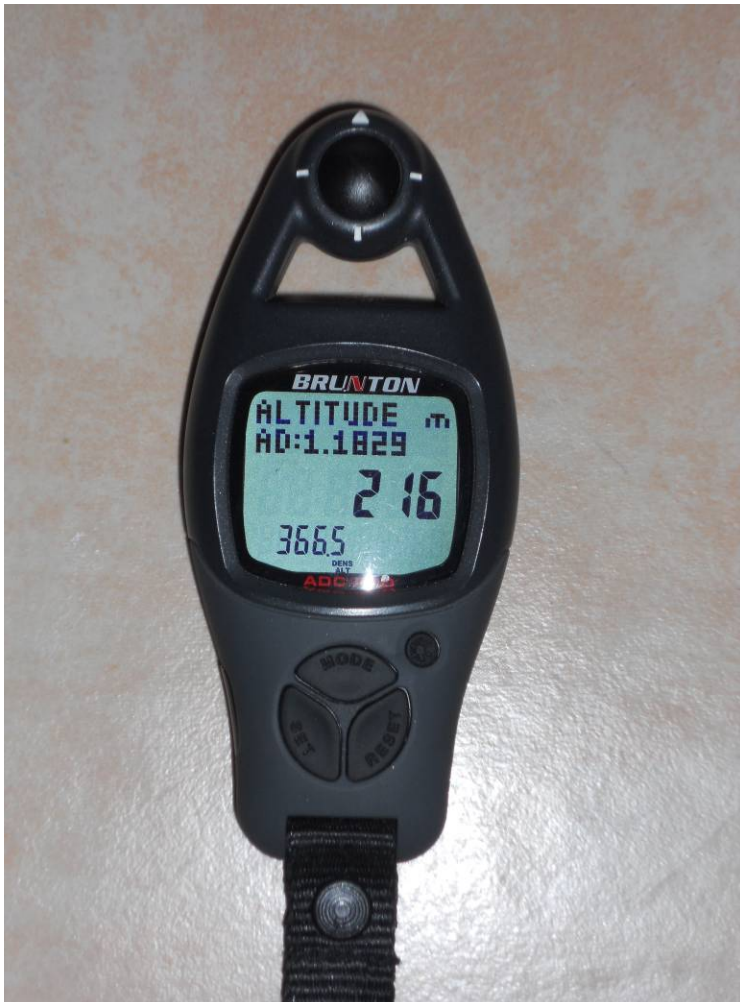
6. *Anemometer*

Flow through the tunnel is measured using an Exetech vane anemometer that I had purchased about 10 y ago for another project. The probe is located in the diffuser just aft of the test section and slightly to one side of the tunnel centerline (to hopefully avoid the wake of any object being tested), as shown in **Fig. 11.** Since the cross-sectional area of the tunnel is greater at this point than in the test section, the corresponding air speed is also lower, requiring correction of the air speed data. Based on Bernoulli's principle, this would mean multiplying the measured air speed by a factor of 1.115 to arrive at the actual air speed in the test section. However, Bernoulli's equation is based on the assumption that there is no loss of kinetic energy as a fluid moves from point A to point B, which would not be strictly correct. Moreover, due to growth of the boundary layer the air flow through the central, working portion of a wind tunnel is gradually compressed into a progressively smaller area, causing it to travel faster than expected (and, in a test section that is wider than it is tall, bend upward, requiring a “buoyancy” correction to any lift measurements). Finally, although I attempted to locate the Exetech probe outside the wakefield of any object being tested, there was still the possibility that the air speed measurements might be affected.

Figure 11. Exetech anemometer used to measure wind tunnel speed.

Because of the above considerations, I decided to use a second vane anemometer (i.e., a Brunton ADC Pro; **Fig. 12**) to derive the necessary correction factor. First, I verified that both instruments read the same when placed in the same location, i.e., within the diffuser just aft of the end of the test section. I then placed the Brunton in the very center of the test section and compared the average wind speed as measured by the two instruments over a 5 min period. This experiment demonstrated that the air speed in the test section was 7.6% higher than in the front part of the diffuser (vs. the 11.5% expected based on theoretical considerations). In other words, to determine the actual air speed directed at an object in the test section, the air speed data provided by the Exetech had to be multiplied by a factor of 1.076. This result is consistent with an essentially-stagnant boundary layer approximately 3 mm thick – that is, the “effective” cross-sectional area of the diffuser where the anemometer probe is located is *apparently* 96,495 mm^2 (i.e., 310.6 x 310.6 mm), vs. the actual cross-sectional area at this point of 98,228 mm^2 (i.e., 313.4 x 313.4 mm). Although I did not perform any formal calculations, this value (i.e., of several millimeters, but less than a centimeter) seems reasonable given the expected turbulence intensity and the rate of air flow through the tunnel.

Figure 12. Brunton ADC Pro used for validation experiments and to routinely measure air density.



In other experiments, I also used the Brunton's data recording ability to determine 1) the unsteadiness of the flow (i.e., fluctuations in speed over periods of time that are long relative to that required for a single "packet" of air to traverse the test section), and 2) the uniformity, or lack thereof, of flow in the test section. These measurements demonstrated an unsteadiness of 0.6% and a non-uniformity (excluding the boundary layer) of <1%, again both comparable to that of many university wind tunnels and in keeping with Marshall's design criteria.

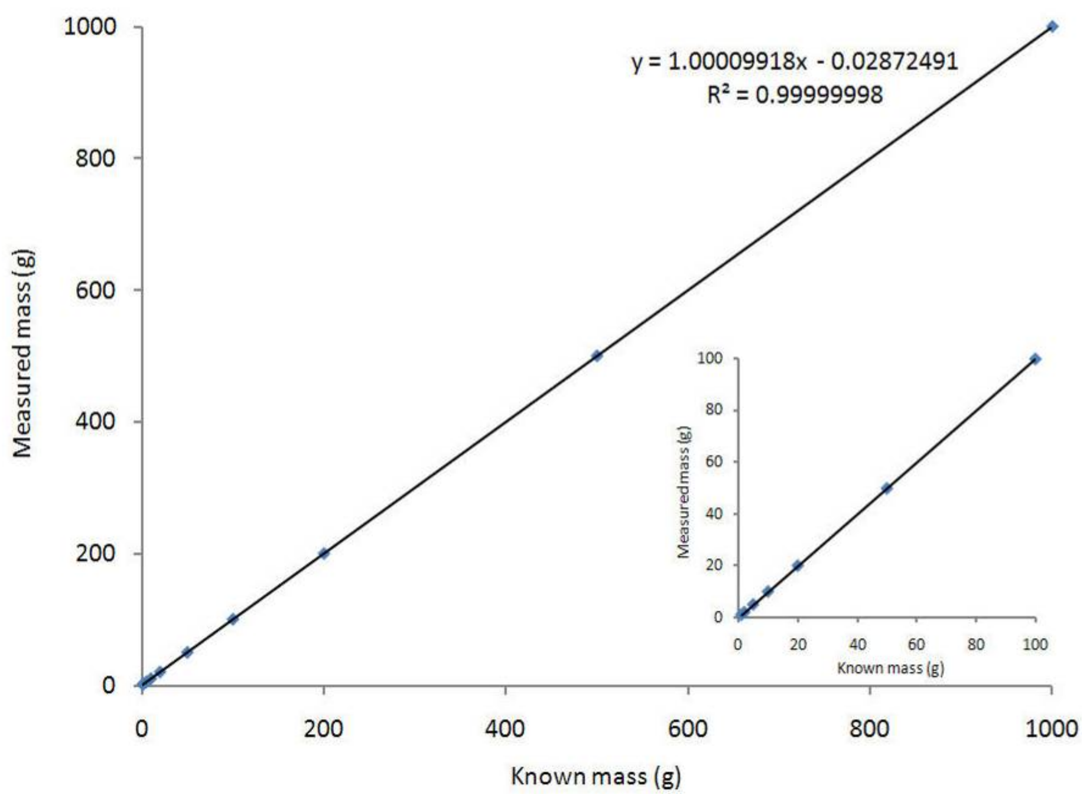
Note that I did not directly verify the absolute accuracy of the Exetech anemometer, but I had previously found the Brunton to read accurately when mounted on a bicycle that was pedaled at a wide range of speeds through very still air (cf. http://www.trainingandracingwithapowermeter.com/2010/10/challenge-to-cycling-aerodynamicists.html). Thus, the close matching between data from the Brunton and the Exetech anemometer when both were placed in the same point in the wind tunnel provides confidence that the Exetech is accurate to within the manufacturer's claims (i.e., to within ±2%).

Finally, the Brunton is also used to measure the density of the air at the time of testing, to allow calculation of CdA (see *Routine Operation*). The accuracy of the device for this purpose was previously established by comparing the temperature, barometric pressure, and relative humidity data provided by the Brunton against those from research-grade instruments (e.g., a mercury-in-glass barometer). On the other hand, the precision of the air density measurements and the speed measurements provided by the Exetech anemometer is demonstrated by the existence of a very close (i.e., $R^2 = 0.96$) inverse relationship between air density and speed[3] even over an extremely small range (i.e., 0.3% for air density and 1.7% for speed) resulting from normal fluctuations in weather.

7. *Balance system*

As mentioned previously, I tried to design the balance system to be 1) simple, so that it could used to help teach elementary mechanical concepts (e.g., leverage), 2) inexpensive, and 3) sensitive. To this end, I first purchased a small scale made by US Balance (for the princely sum of $13) and determined its accuracy and linearity using an Ohaus balance calibration kit left over from my undergraduate chemistry days. To my delight, this inexpensive balance performed wonderfully, as demonstrated by the data in the **Fig. 13** below.

Figure 13. Validation of scale incorporated into balance system.



Having verified the functioning of the balance, I incorporated it into a cable-and-pulley system as shown in **Fig. 14** and **Fig. 15** below. The small and large brass weights are from the Ohaus kit, whereas the sealed bearing pulleys were scavenged from a pair Travel Agent brake boosters that were originally on our tandem. For the cables, I used 50 lbs nylon fishing line. An eye screw threaded through a nut epoxied to the large weight allows easy adjustment of the position of the sting, which the smaller weight helps hold in a vertical position when the tunnel is off. Along the same lines, the pivot is held to the base via an L-shaped bracket and a small knob, such that the yaw angle can be quickly changed. Finally, the points of attachment of the cables and of the object being tested were placed such that the aerodynamic drag force is multiplied by a factor of 2.5 prior to measurement by the scale. The minimal force resolution of the balance system is therefore 0.1 g/2.5 x 9.805 N/1000 g = 0.000392 N. Along with the quality of the air flow and hence the precision (reproducibility) of the measurements, this makes it possible to detect very small differences in aerodynamic drag (see below).

Figure 14. Schematic diagram of balance system.

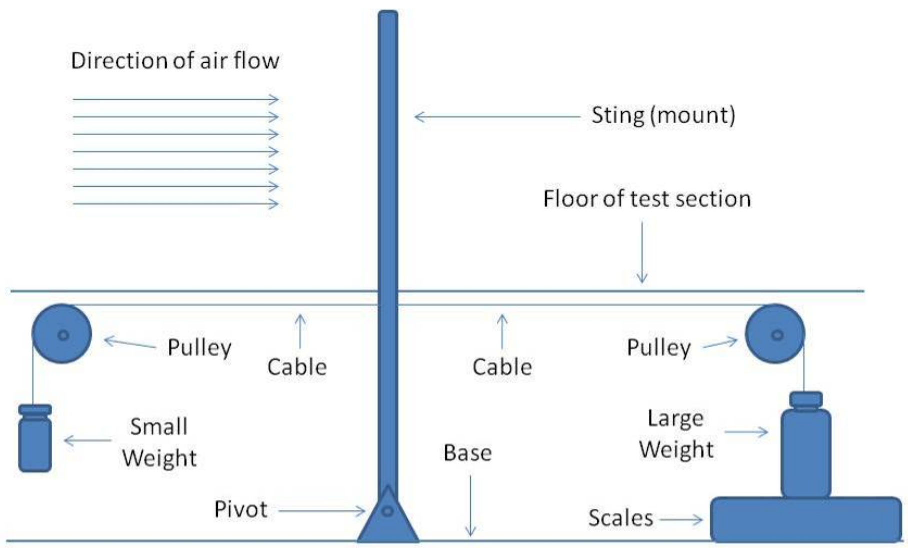


Figure 15. Photograph of balance system.

Validation

The process typically followed when commissioning a new wind tunnel for use is to carefully determine:

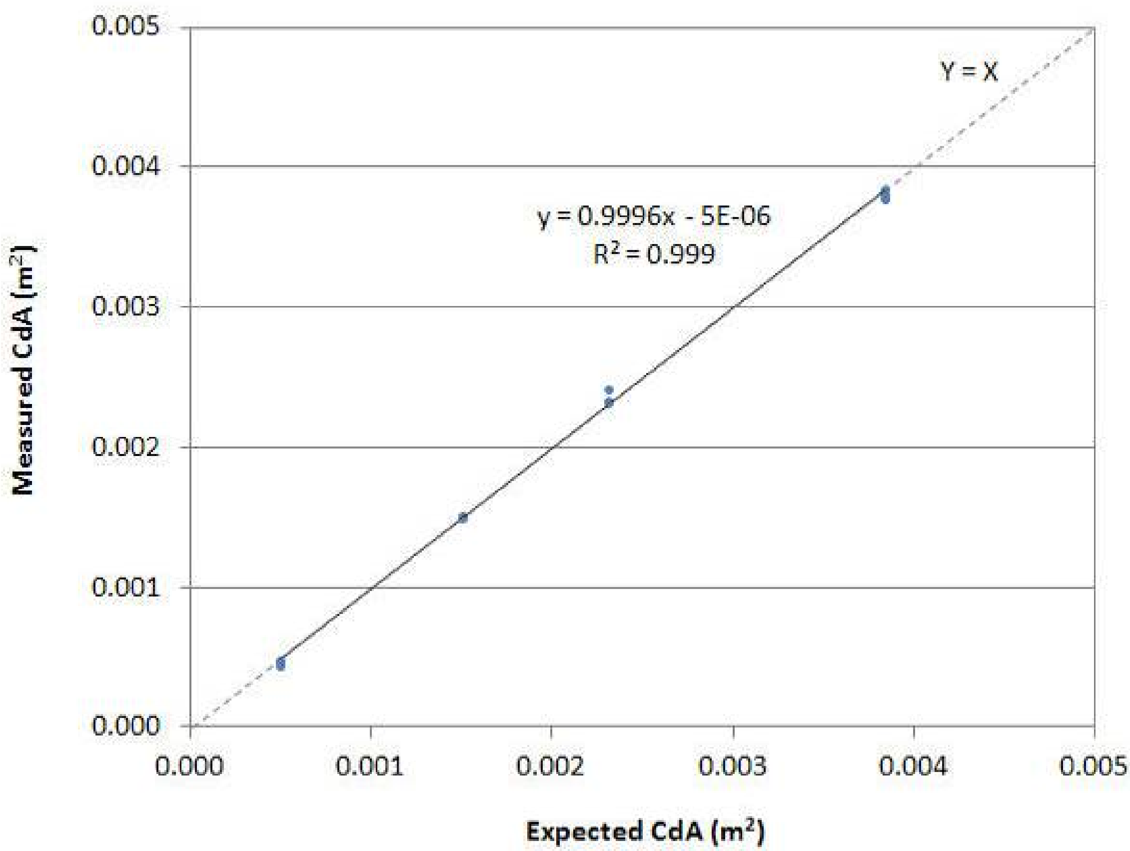
1) the steadiness, homogeneity, and angularity of the flow;
2) the intensity of the turbulence;
3) the size and growth of the boundary layer;
4) the accuracy and precision of associated instrumentation (e.g., pressure sensors, the wind tunnel balance), etc.

As described previously, I was able to complete a number of these steps, but lacked the instrumentation necessary to perform others. In particular, I was not able to measure the angularity of the flow or the turbulence intensity, as to do so would have required a hot wire anemometer capable of recording data at ≥8 Hz (at 7.5 m/s, it would take a "packet" of air 0.081 s to traverse the 0.61 m long test section – fluctuations in flow occurring over more than twice this duration would be considered unsteadiness, not turbulence). Thus, despite the fact that I followed well-accepted design principles and all of the measurements that I *could* make were within accepted limits, I could not be absolutely certain that I had constructed a wind tunnel capable of producing highly precise and accurate data. I therefore decided to attempt to validate the tunnel by measuring the CdA of spheres of different sizes, and comparing the results obtained to those theoretically expected. The spheres (balls) that I used ranged in size from 37.5 to 101.6 mm in diameter (**Fig. 16**).

Figure 16. Balls used to calibrate/validate wind tunnel.

The results of this experiment demonstrated a close matching between the measured and expected values for CdA, as shown in **Fig. 17**.

Figure 17. Relationship between expected and measured CdA for the four balls shown in Fig. 16.



Since I tested each sphere three times, this experiment also allowed me to determine the overall precision of the CdA measurements. As implied by the close clustering of points in the figure above, the calculated CdA values proved to be highly reproducible, with an average standard deviation of just 0.0000263 m^2 (i.e., CV = 2.0% - see Table 2). Indeed, the data were so precise that I was able to spot that I had initially made an error (of 1.7 mm) when measuring the diameter of the next-to-largest sphere, causing the expected CdA to be 4% too low!

Routine Operation

The exact steps used to collect data using the tunnel may vary with the object being tested, etc., but in general the procedure is as follows:

1) the object is attached to the sting (or mount) so that it is positioned in the center of the test section;
2) the desired yaw angle is set by loosening the knob holding the bracket to which the sting is attached, rotating the bracket to the desired angle (checked using a carpenter's square against alignment guides drawn on the base), and retightening the knob;

3) the length of the fishing line connecting the sting to the larger weight sitting on the balance is adjusted, via the eyescrew, so that the sting is directly centered in the hole in the floor of the wind tunnel. If the object to be tested unbalances the system to such an extent that this cannot be achieved, the front counterweight is replaced by a larger or smaller mass as required;
4) the balance is tared (with the larger weight sitting on it);
5) the fan is turned on and the wind tunnel allowed to operate until a steady reading is obtained on the balance (depending on the size/mass/aerodynamic properties of the object being tested, the balance reading may regularly fluctuate by a small amount, necessitating an “eyeball” interpolation.);
6) over a 1 min period, the average wind speed is measured using the Exetech anemometer’s memory function, during which time the balance is periodically observed to make sure that the reading does not change;
7) these data (i.e., drag force and wind speed) are recorded along with the air density at the time of testing as measured using the Brunton ADC Pro;
8) the fan is turned off and the balance observed to see if it returns to the initial tare value (i.e., 0.0 g). If it does not, the new “wind off” tare is recorded and subtracted from the measured drag to account for this drift of the balance (due to vibration);
9) the recorded data are used to calculate CdA via a spreadsheet (see Table 2 for sample printout), correcting for blockage using the “momentum method”, i.e., by assuming that the kinetic energy of the air in the test section remains constant, such that it must accelerate as it “squeezes past” the object being tested. (Although more sophisticated wind tunnel data correction methods exist, the momentum method has been shown to be adequate when measuring the drag of simple objects that result in a blockage of less than 6%.)

References

Listed below are some of the references that I consulted in the process of designing and building the wind tunnel. This list is by no means comprehensive, however, so I suggest that anyone reading this document who is considering building their own wind tunnel perform additional research before embarking on such a project.

Books

Barlow JB, Rae WH, Pope A (1999). Low-speed wind tunnel testing, 3rd ed. John Wiley & Sons: New York, NY. ISBN-13: 978-0471557746

The classic book reference, but expensive to buy and likely to be found only in a university (vs. public) library.

Journal articles

Johl G, Passmore M, Render P (2004). Design methodology and performance of an indraft wind tunnel. Aeronaut J: 465-473.

The above article provides a highly detailed description of the design, construction, and performance of a modern university wind tunnel. It is well worth reading if only for the logical manner in which the authors approach the subject.

Marshall RD (1985). Performance requirements and preliminary design of a boundary layer wind tunnel facility. National Bureau of Standards U.S. Department of Commerce Rep. No. NBSIR 85-3168.

This government report contained suggested standards for wind tunnel performance.

Mehta RD, Bradshaw P (1979). Design rules for small low speed wind tunnels. Aeronaut J: 443-449.

A brief synopsis of many of the same design guidelines the authors provide via their website (see below).

Sargison JE, Walker GJ, Rossi R (2004). Design and calibration of a wind tunnel with a two dimensional contraction. Proceedings of the 15th Australasian Fluid Mechanics Conference, The University of Sydney, Australia.

I relied on this paper for the design of the contraction.

West GS, Apelt CJ (1982). The effects of tunnel blockage and aspect ratio on the mean flow past a circular cylinder with Reynolds numbers between 10^4 and 10^5. J Fluid Mech: 361-377.

A paper evaluating different wind tunnel data correction methods.

Internet sites

http://www.sciencebuddies.org/science-fair-projects/wind-tunnel-toc.shtml

This detailed description of how to build your own wind tunnel was my primary source of inspiration, especially for the design and construction of the diffuser and (at least initially) the test section. There is also a sub-section of the Science Buddies forum devoted to this project, where I was able to get some useful feedback directly from the person who designed and built the tunnel (which, interestingly, is housed in a high school in suburb nearby to the one in which I live).

http://www.fi.edu/flights/first/makebigger/index.html

Another very useful "how-to" site. It was from here that I got the idea to build the contraction out of mat board (although I used packing tape instead of fiberglass to reinforce the joints).

http://navier.stanford.edu/bradshaw/tunnel/index.html

This is Bradshaw and Mehta's (or Mehta and Bradshaw's) website, which contains much succinct advice and discussion and so was an excellent place to start my reading.

http://www.fbs.leeds.ac.uk/staff/Rayner/Flight/wtdbzwjm.htm

Description of a representative university wind tunnel.

http://www.grc.nasa.gov/WWW/K-12/airplane/bgt.html

This NASA website contains many useful links and much helpful information.

http://www.ma.iup.edu/projects/CalcDEMma/drag/drag0.html

This is the reference I used for the expected drag of a sphere as a function of Reynolds number.

Acknowledgements

I would like to sincerely thank my adventuresome daughter, Madeleine, for providing the impetus for this project, and her, my rambunctious son Gavin, and my lovely wife Angie for putting up with my enthusiasm for geeky endeavors such as this one.

TABLE 1. DIMENSIONS AND OPERATING CHARACTERISTICS

Overall	
Height (maximum) (mm)	648
Width (maximum) (mm)	635
Length (mm)	2454
Inlet/Settling chamber	
Height (mm)	610
Width (mm)	610
Length (mm)	155
Honeycomb	
Cell diameter (mm)	3.175
Cell length (mm)	25.4
Length:diameter	8:1
Number of cells (approx.)	36,000
1st Screen	
Aperture height (mm)	2.74
Aperture width (mm)	2.74
Wire diameter (mm)	0.43
Open area (%)	74.6
Pressure drop coefficient (unitless)	1.39
Turbulence intensity reduction factor (unitless)	0.42
2nd Screen	
Aperture height (mm)	1.31
Aperture width (mm)	1.13
Wire diameter (mm)	0.28
Open area (%)	66.1
Pressure drop coefficient (unitless)	2.24
Turbulence intensity reduction factor (unitless)	0.31
Contraction	
Height at entrance (mm)	610
Width at entrance (mm)	610
Height at exit (mm)	305
Width at exit (mm)	305
Entrance area:exit area	4:1
Length (mm)	610
Distance from entrance to point of inflection (mm)	366

Test Section

Height (mm)	305
Width (mm)	305
Length (mm)	610
Normal operating speed (m/s)	7.5
Reynolds number	2.56×10^5
Flow unsteadiness (%)	0.6
Flow non-uniformity (outside of boundary layer) (%)	<1
Turbulence intensity (theoretical) (%)	0.2 – 0.6

Diffuser

Height at entrance (mm)	305
Width at entrance (mm)	305
Height at exit (mm)	423
Width at exit (mm)	423
Entrance area:exit area	1.9:1
Length (mm)	1218
Included angle (vertical or horizontal) (deg)	5.5

Fan

Brand/model	Ventamatic/CX2500
Blade diameter (mm)	356
Motor amperage (amps)	2.1
Capacity (claimed) (ft^3/min)	1650

Anemometer

Brand/model	Exetech/407112
Speed range (m/s)	0.0 – 25.0
Minimal resolution (m/s)	0.1
Accuracy (claimed) (%)	±2

Balance System

Brand/model of balance	US Balance/Magnum 1000XR
Maximum capacity (g)	1000
Minimal resolution (g)	0.1
Accuracy (measured) (g)	Better than ±0.1
Distance from sting pivot to center of working section (mm)	250
Distance from sting pivot to counterweight attachment (mm)	100
Drag force amplification ratio	2.5:1
Maximum capacity of drag force measurements (N)	24.5
Minimal resolution of drag force measurements (N)	0.000392
Accuracy (measured) (N)	Better than ±0.000392

TABLE 2. EXAMPLE OF CALCULATIONS USING DATA FROM VALIDATION EXPERIMENT

				blockage				speed			Balance reading			CdA (m^2)				
Date	object	diameter (mm)	frontal area (m^2)	blockage (%)	correction	air density (g/L)	(ft/min)	corr. factor	(m/s)	Re	Wind on (g)	Wind off (g)	Delta (g)	expected	measured	average	SD	CV
11/13/2011	sting	n/a	n/a	n/a	n/a	1.1887	1359	1.076	7.43	n/a	1.4	0	1.4	n/a	n/a			
	ping-pong ball	37.5	0.00110	1.2%	1.0119	1.1953	1363	1.076	7.45	1.87E+04	6.4	0.5	5.9	0.00050	0.00049			
		37.5	0.00110	1.2%	1.0119	1.1881	1360	1.076	7.43	1.85E+04	5.7	0.0	5.7	0.00050	0.00047			
		37.5	0.00110	1.2%	1.0119	1.1958	1363	1.076	7.45	1.87E+04	5.5	0.0	5.5	0.00050	0.00044	0.00047	0.00002	4.7%
	small ball	64.5	0.00327	3.5%	1.0352	1.1957	1360	1.076	7.43	3.20E+04	17.3	1.7	15.6	0.00150	0.00151			
		64.5	0.00327	3.5%	1.0352	1.1957	1363	1.076	7.45	3.21E+04	15.6	0.0	15.6	0.00150	0.00150			
		64.5	0.00327	3.5%	1.0352	1.1965	1361	1.076	7.44	3.21E+04	15.6	0.0	15.6	0.00150	0.00151	0.00151	0.00000	0.2%
	large ball	79.5	0.00496	5.3%	1.0534	1.1976	1365	1.076	7.46	3.97E+04	26.6	1.9	24.7	0.00231	0.00241			
		79.5	0.00496	5.3%	1.0534	1.1983	1372	1.076	7.50	3.99E+04	25.8	1.6	24.2	0.00231	0.00233			
		79.5	0.00496	5.3%	1.0534	1.1969	1365	1.076	7.46	3.97E+04	24.3	0.5	23.8	0.00231	0.00232	0.00235	0.00005	2.1%
	foam ball	101.6	0.00811	8.7%	1.0873	1.1945	1365	1.076	7.46	5.06E+04	34.7	-4.3	39.0	0.00384	0.00378			
		101.6	0.00811	8.7%	1.0873	1.1950	1361	1.076	7.44	5.04E+04	40.3	0.9	39.4	0.00384	0.00384			
		101.6	0.00811	8.7%	1.0873	1.1975	1362	1.076	7.44	5.06E+04	39.6	0.4	39.2	0.00384	0.00381	0.00381	0.00003	0.8%
																	0.0000263	2.0%